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Microwave Photonics in Dual-Use Military Systems - A Personal Perspective

Afshin S. Daryoush
Department of Electrical and Computer Engineering
Drexel University, Philadelphia, PA 19104, USA

Daryoush@ece.drexel.edu

Abstract

Microwave photonics has come of age and there are a number of military applications that could directly benefit from. Optically controlled phased array antenna is one of the most widely pursued applications. The fiberoptic links are employed for distribution of a variety of communication, intelligence, tracking, radar signals. There are a number of issues that dictate the type of architecture that is employed for effective and reliable control of phased array. However, the most important benefit is in the optical signal processing of microwave signals. Fiber delay lines are an important element of an signal processing solutions.

1. Introduction

The last two decades of 20^{th} century with significant advances of IC technologies and proliferation of commercial fiberoptic communication technologies, a gradual acceptance of microwave photonics is being experienced in the most conservative military circles. However, the question still remains whether microwave photonic techniques could fulfill its claim to deliver all the benefits, which were touted in many circles in late 1970's. Figure 1 depicts a conceptual representation of my personal view of future combat systems, where special operation units and low flying air vehicles are linked to the global information network using low profile wireless local area networks. The challenges that military system planners encounter are somewhat similar to the commercial needs that are being driven by consumers. In essence, except for a much higher reliability requirements imposed for the military operations in hostile environments, both civilian and military systems overlap in many technical aspects.

Among many aerospace and military applications of fiberoptic technology, none have received the same level of attention and support from technical and government as the concept of optically controlled phased array antenna systems. A historical perspective of phased array antenna evolution is depicted in Fig. 2, where a significant amount of electronics is distributed in the entire aperture. In fact, MMIC based active phased antennas are designed for radar, tracking, communication, and electronic warfare (EW) applications and still it appears that the role that photonics could play in this arena is not quite clear. It was recognized then and still considered that future demands for multibeam shared aperture phased array antennas could not be achieved without incorporation of significant amount of processing, control, and communication capability at each active array element. It is clear as the information throughput significantly increases, there is need for ultra high-speed fiberoptic links to transfer data, where standard electrical interconnect fails due to poor EMI, dispersion, loss, and large size. Both analog and digital fiberoptic links are crucial part of interconnects in any distributed system.

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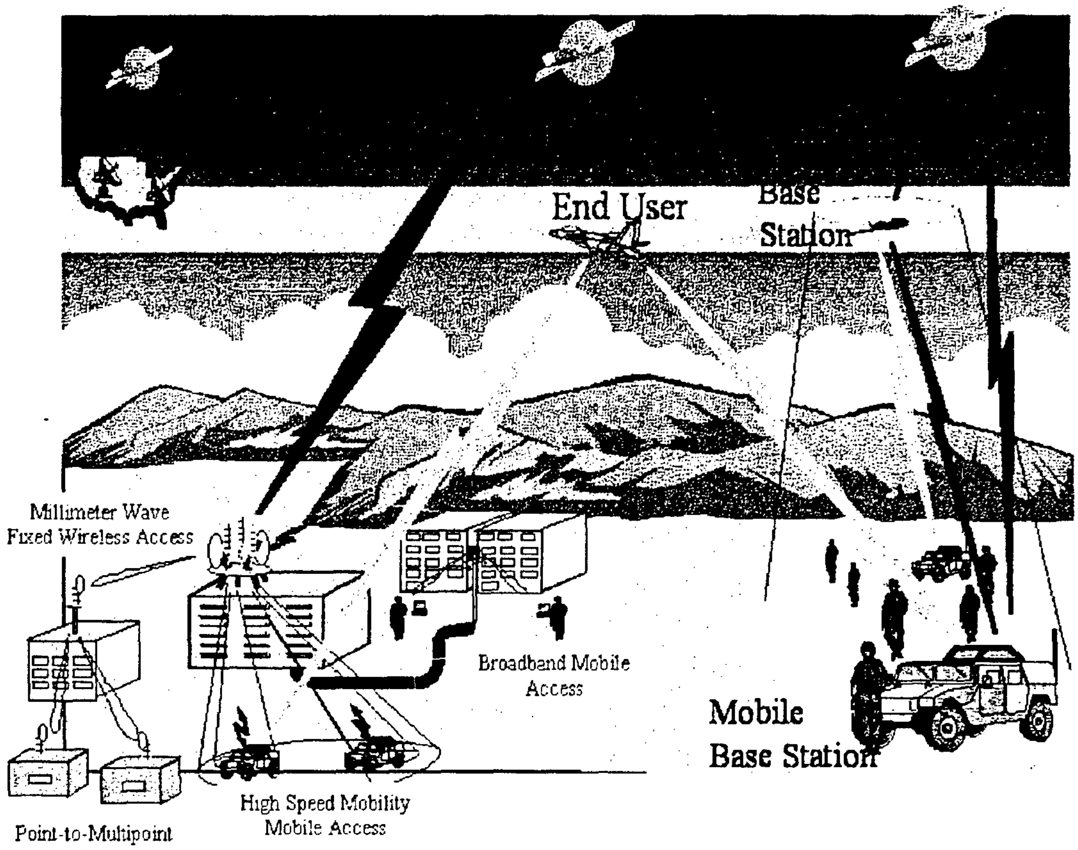


Fig. 1. Conceptual representation of a number of wireless networking used for Comm-on-the-Move for Future Combat Systems.

Conceptual representation of a shared aperture antenna for surface Navy vessels is depicted in Fig. 3, where the antennas and electronics for a variety functions are co located. In this figure, other conventional antenna structures are also depicted for comparison, where linear arrays (for L-band radar) and reflector antennas (for S-, C-, X- band radar, and C-band communication) are employed. One of challenges is efficient distribution of the modulated carrier, particularly at Ka-band frequencies and above. Performance of optical components in harsh military environment is discussed first followed with packaging issues that could reduce cost of optical alignment. Furthermore, phase and amplitude of the radiating element should be controlled in real-time to scan and shape the radiated beam in a particular direction. In multibeam phased array systems, beams are shaped for different directions in space at various operation frequencies. Both analog and digital beamforming networks has been demonstrated, however with advent of high-speed DSP it becomes more attractive to pursue the latter. Furthermore, it is predicted that future threats will employ EW measures to defeat the effectiveness of electronic support attained from multi-sensors. Therefore, electronic counter measures (ECM) based on radar warning receivers (RWR) are required to engage simultaneously a number of active threats. In my opinion the optical signal processing is where clearly advantages of photonic system become evident. Fiber optic delay lines are employed to generate memory devices, interference cancellation, and narrow bandpass filters.

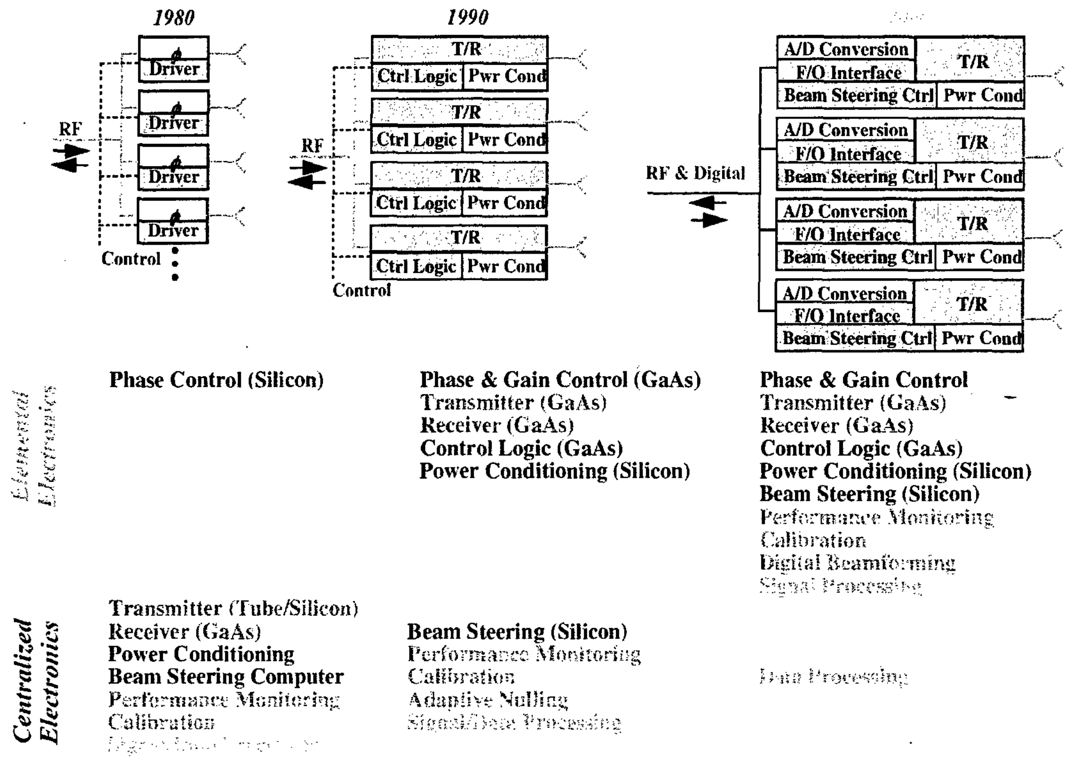


Fig. 2. A historical timeline presented evolution of phased array antennas in the last three decades. Note in this vision both MMIC and FO technologies are an integral part of future phased arrays.

Table I shows a composite of frequency bands allocated for radar, communication and EW systems. For a viable multifunction electronic systems to be used in the future shared aperture antennas, a distribution network are required to provide coherent signals to the T/R modules. Note that the desired RF signals could be obtained using mixing of the data signal with a stabilized local oscillator, as indicated in the column dealing with the *"FO link realization"*. Therefore, to realize a coherent front-end receiver and transmitter in phased arrays, each optically fed antenna should have its own antenna mounted front end electronics, which is composed of opto-electronic interface circuits, stabilized local oscillators up to the MMW frequencies, and efficient mixers. Various techniques that enable optical generation of MMW signals and opto-electronic mixing have been developed and a few are being presented as part of this lecture series by Professors Berceli, Cabon, and Jaeger. Author will also present phase noise coherency and opt-electronic mixing capability of fiberoptic links in an accompanying paper in this proceedings. Moreover different methods of building active phased array antennas are discussed by other presenters Chazelas and Lee.

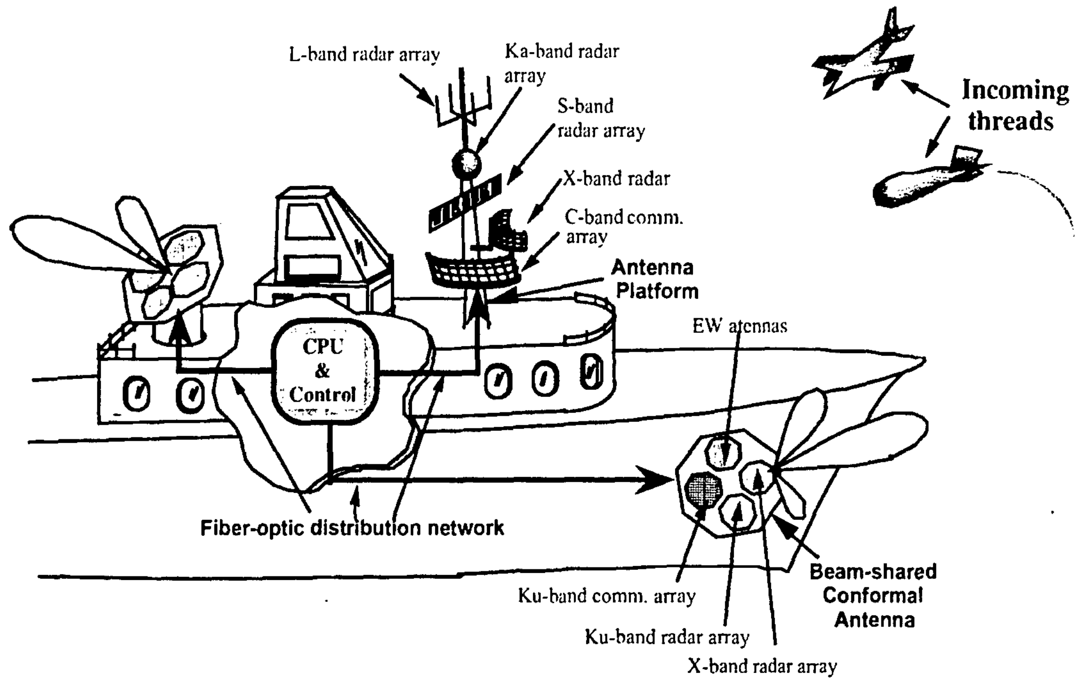


Fig. 3. Conceptual block diagram representation of a future generation of AEGIS cruiser with shared aperture concept, capable of radar, tracking, communication, and EW functions such as direction finding up to MMW.

Frequency band	Radar	Communication	EW	FO links Realization
L-band	2 - 3 GHz		≥ 2 GHz	**Radar**: 2-3 GHz FO link **EW**: 200MHz - 18 GHz FO link
C-band	5.2 - 5.8 GHz	4.2 -5.2 GHz	Entire band 4-8 GHz	**Radar** LO: 6GHz; IF: 200-800MHz **Comm.**LO: 6GHz;IF: 800-1300 MHz **EW:** 200MHz - 18 GHz FO link
X-band	9 - 10 GHz		Entire band 8- 12 GHz	**Radar** LO: 12 GHz; IF: 2-3 GHz (Lower sideband) **EW:** 200MHz - 18 GHz FO link
Ku-band		14 - 15 GHz	Entire band 12 -18 GHz	**Comm.** LO: 12 GHz ; IF: 2 - 3 GHz (Upper sideband) **EW:** DC - 18 GHz FO link
K-band			Entire band 18 - 30 GHz	**EW** LO: 12 GHz; IF: 6 - 18 GHz
Ka-band	33 - 34 GHz	21 - 22 GHz	Entire band 30 -42 GHz	**Radar** LO: 36 GHz; IF: 2 - 3 GHz; **Comm.** LO: 24 GHz; IF: 2 -3 GHz; **EW** LO: 24 GHz; IF 6-18 GHz

Table I. Composite of frequency band allocations for radar, communication, and EW for shared aperture systems.

3.0 Fiberoptic Distribution for Phased Array Antennas

One of the simplest methods of providing FO links for antenna remoting is based on the concept of direct replacement of the electrical interconnects. However, there are challenges associated with reliability of optical components, cost of system integration, and the architecture employed for achieving the best attributes possible.

Device Innovations and Reliability: A vast number of research work reported in literature have focused on the device improvements to meet the performance requirement of commercial fiber optic communication. Performance of sampled directly and externally modulated fiber optic links operating at S-band is rendered in Table II, where the best performance is achieved. For DFB laser monolithically integrated with EA modulator. The performance of mode-locked laser is quite acceptable (The results of MZ modulator may appear worse than what is reported in literature, but in this case a semiconductor laser with optical power of only a few mW is used as a source. Monolithically integrated EA modulator with sampled grating DBR laser (SGDBR) [1] has been developed where SFDR of 120 dB.Hz$^{2/3}$ is achieved over a large tuning bandwidth. However, the harsh military environment impose additional burden on the performance of lightwave technology components.

	Directly Modulated FO Links		Externally Modulated FO Links	
	Mode-Loked Laser	Ortel DFB Laser	DFB/EA Modulator	Sumitomo MZ Modulator
Frequency	**2.2GHz**	**2.5GHz**	**2.2GHz**	**2.5GHz**
Gain (dB)	-8	-44	-12	[illegible]
IP3 (dBm)	[illegible]	[illegible]	[illegible]	[illegible]
Noise Floor (dBm/Hz)	**-142**	**-151**	**-151**	**-151**
SFDR (dB.Hz$^{2/3}$)	[illegible]	86	[illegible]	90

Table II. Comparison of various COT fiberoptic links at S-band. Note the MZ modulator is based on DFB laser as optical source.

Table III compares performance of passive optical components under harsh radiation and temperature environment of space. As result of extreme temperature variation, micobending losses will impact performance of fiber based products, whereas on insulated waveguide pyroelectric effect introduces change in coupling factor. Moreover radiation impacts losses due to absorption (i.e., generation of coloring centers) in optical fibers and coupling losses due to change in index of refraction as result of photorefractive effect in insulated waveguides. On the other hand, semiconductor based optical sources and amplifiers suffer from change in bandgap due to temperature variation, whereas the Er: doped fiber amplifiers (EDFA) suffer from the similar characteristics as optical fibers. There have not been any siginifcant studies on the impact of temperature variation on EA modulator and photodetectors, but one can predict that there will changes in bandgap and hence resulting in

shift in absorption edge. The impact of radiation on semiconductors is increase in shot noise and change in absorption bandedge in photodiodes and EA modulators. Optical sources and amplifiers suffer from change in gain, hence modifying its dynamic performance. Naturally, there are proposed solutions associated with each problem. Due to impact of radiation and temperature on insulated based waveguides, I will not focus on the MZ based system in the remaining discussions.

		Silica Fiber				Insulator WG	
		SM	PM	Cables	Couplers	Couplers	Modulators
Radiation	**Damage**	**Coloring Center**			**Absorption**	**Photorefractive**	
	Impact	Optical Loss			Coupling	Coupling	
	Solution	Rad Hard Fiber			Shielding	Shielding	
Temperature	**Damage**	**Stiffness**			**N/A**	**Pyro-electric**	
	Impact	Microbending Loss			N/A	Coupling Factor	
	Solution	Material/Internal			N/A	Temperature Control	

Table III. Reliability of passive optical components in harsh environment of space.

		LED	LD	SOA	Er:Doped	Photodiode	EA Modulators
Radiation	**Damage**	**Recombination Center**			**Absorption**	**Electron-Hole**	
	Impact	Loss	Gain		Gain	Shot Noise	Band Edge
	Solution	Higher Bias Current			Rad Hard	Shielding	
Temperature	**Damage**	**Bandgap**			**Stiffness**	**N/A**	
	Impact	Gain			Microbending Loss	N/A	
	Solution	Internal/Temperature Controller			Internal	N/A	

Table IV. Reliability of active optical components in harsh environment of space.

Packaging Requirements: As indicated in the accompanying paper on fiberoptic link, a dB improvement in the optical coupling improves insertion gain by a 2dB. However, mechanical tolerances of optical fibers and sources are in sub-micron range, hence making the low cost integration of optical components with optical fibers challenging the least. More over this process has to be done in a cost effective manner. Another important aspect of the light coupling is that reflection has to be minimized since any optical feedback introduces modulation of the dynamic response which resembles the transmission characteristics of FP resonators. Therefore, optical isolators combined with angle polished fibers are required to reduce the light feedback level below 50 dB in certain applications. Another important aspect is temperature control of semiconductor devices to avoid any sensitivity to temperature in

harsh environments of space. Finally, directly modulated fiber optic links or externally modulated systems using EA modulators, experience input impedance that corresponds to high reflection coefficients (i.e., approximately short for laser diode and open for EA modulator). To avoid high reflection loss, impedance matching circuits are needed to be developed, which is not easy to accomplish over a large fractional bandwidth. Fig. 4 depicts a designed structure of monolithically integrated optical source with EA modulator [2], which is used for distribution of both LO signal and data signal.(The details of this source performance is presented in an accompanying paper dealing with FO links.) This structure is also based on cascading a number laser with monolithically long FP cavity in series, hence increasing the forward P-N junction resistance, while maintaining the same RF current modulating all the gain sections. In essence, since the input impedance of laser diodes is of forward biased P-N diode is about 4Ω, by series combination of the impedance a level closer to 50 Ω is achieved. Moreover a lower Q_{ex} factor is obtained, which simplify the matching circuit design. Finally, the fiber coupling is achieved cost effectively by combining a number of lensed fibers mounted on a silicon V-groove. This process will enable packaging a large number of laser diode sources.

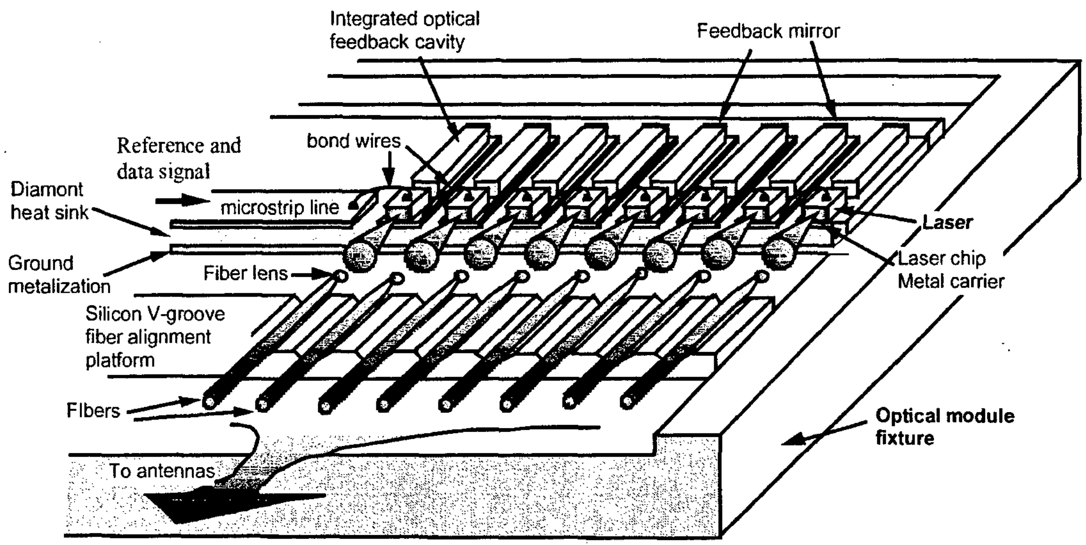


Fig. 4. Conceptual representation of an optimized optical transmitter using eight series mounted laser diodes with monolithically integrated external optical cavity coupled to the lensed fibers using a Si V-groove fiber alignment system.

Architecture Innovations: In large aperture phased array antennas, RF signal could be down converted to the IF signals for further processing at the centralized receiver. This architecture, shown in Fig. 5, is the conventional one. The challenges for implementation of optically controlled phased array using this architecture are: i) a high dynamic range fiber optic links are required at ultra-high frequencies, ii) phase and frequency control needs to be maintained in the distribution network all the way to the central processor, 3) as will be shown a higher resolution for true time delay device are required. On the other hand, the T/R Level Data Mixing architecture, shown in Fig. 6, provides a great opportunity to perform down conversion of the RF signals to IF and avoid the limitations that are encountered in the CPU level data mixing. The additional cost are: i) the need for stabilized LO at each element to coherently down- or up-convert the received RF or IF signals; ii) increase in the number of optical links; iii) the requirement of phase control in addition to TTD to obtain squint free

radiated beam. Nonetheless, experimental comparison of a 2x4 MMIC based C-band phase array antenna was conducted, where a superior dynamic range was measured for T/R level data mixing architecture over the CPU level one [3]. These apparent limitations were avoided using cascaded ILPLL oscillator [4], self-oscillating mixer [5], opto-electronic mixer using MLL [6]. The most important advantage of T/R level data mixing is its reduction of the number of resolution bit required to generate a squint free beams. This issue is highlighted next.

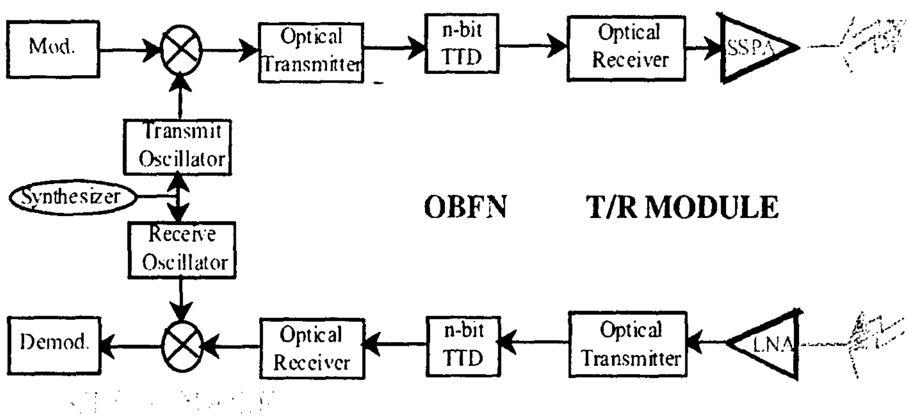


Fig. 5. CPU Level Data Mixing architecture for transmit and receive mode operation. Note true time delay devices are required for broadband operation without beam squint.

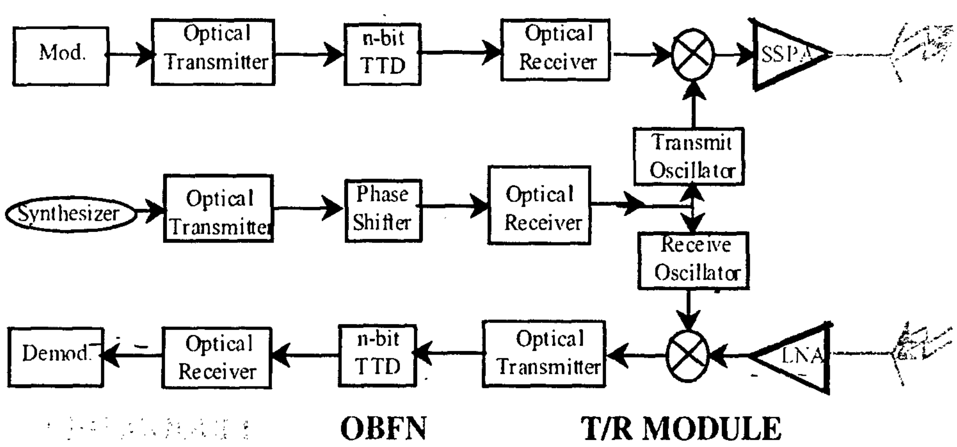


Fig.6. T/R Level Data Mixing architecture for transmit and receive mode operation, where distributed local oscillators need to be synchronized to a frequency reference. Note both true time delay and phase shifter devices are required for beam squint free operation in broadband systems.

Fig. 7 depicts radiation pattern of a 25 element linear phased array (with $\lambda/2$ separation) designed for operation at center frequency of 33 GHz with bandwidth of 3 GHz (i.e., each graph is composite of three simulated graphs at frequencies of 31.5, 33, and 34.5 GHz). The simulation results are for a CPU level data mixing. The required time delay is

achieved using a switched delay line TTD (true time delay device) with minimum time resolution of 10 ps. As this simulation result indicates as the beam is pointed away from broadside, sidelobe levels increase to only -6dBc and the main beam decreases by 2dB. On the other hand, Fig. 8 depicts the simulated performance of the same phased array when it is constructed based on T/R level data mixing. This structure employs a 2π analog phase shifter based on the concept of cascaded oscillators [4] along with a TTD with a time resolution of 30 ps (i.e., decreasing the time delay number of bits by about factor of 4). As this figure clearly represents no reduction in main beam peak level or the increase in side-lobe levels is observed for any scan angles. In fact, the sidelobe levels are compatible with the expected theoretical level of 13.6 dB for uniform array.

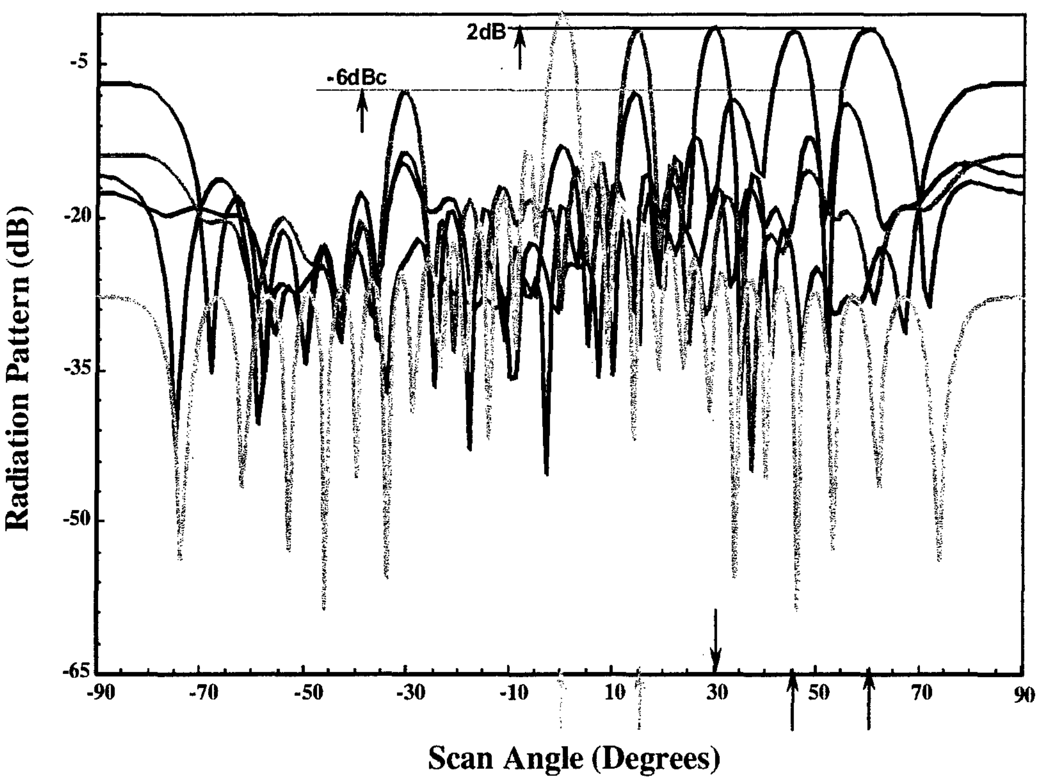


Fig.7. Simulated radiation pattern of 25 radiating element linear multibeam phased array antenna based on a CPU Level Data Mixing architecture where a true-time delay line with10 ps resolution is employed to generate beams at different angles (f_{LO}=24 GHz, f_{data}=7.5 – 10.5 GHz, f_{RF}=31.5 – 34.5 GHz).

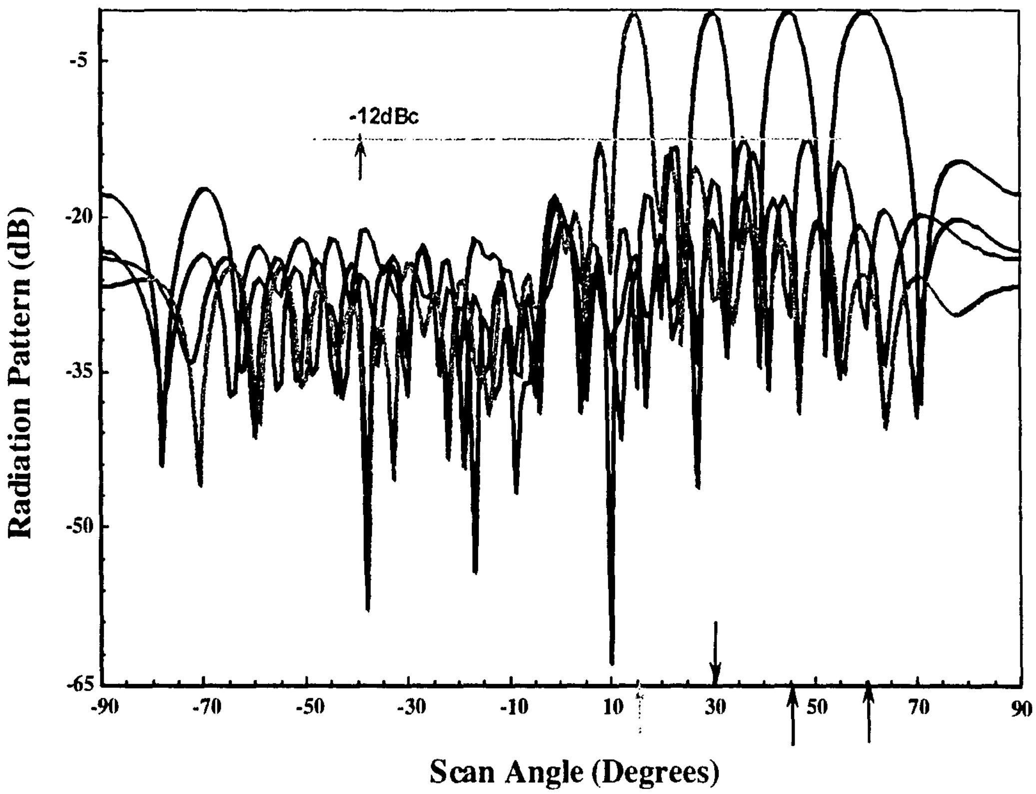


Fig. 8. Simulated radiation pattern of 25 radiating element linear multibeam phased array antenna based on a T/R Level Data Mixing architecture where a true-time delay line with 30 ps resolution along with analog phase shifter for LO is employed to generate beams at different angles (f_{LO}=24 GHz, f_{data}=7.5 – 10.5 GHz, f_{RF}=31.5 – 34.5 GHz).

4.0 Microwave Photonic Signal Processors

One of the most significant advantages of microwave photonics is not the antenna remoting concepts, rather the opportunity to perform signal processing in optical domain. The primary figure of merit is the time bandwidth product that could exceed 10^4, hence leading to significant rejection and filtering using various delay lines. A few realizations of signal processors using microwave photonic techniques are discussed next.

Memory Loop: Fiber optic based memory loops are used for recirculation of the incoming RF pulses. The simplified schematic diagram of a fiber optic based recirculating memory loop is conceptually shown in Fig. 9. This system consists of four basic elements: a switch, an electrical amplifier, a fiberoptic time delay element, and a gain equalizer. The gain equalizer in our system is composed of a YIG tunable filter and an attenuator. The RF input pulse is routed through the switch to the time delay device. The switch closes the loop and thus controls the recirculation. As the signal reenters the microwave circuit, it is amplified and rerouted through the fiber. As a result, a pulse train is obtained that has a pulse repetition interval corresponding to one recirculation time through the loop.

The number of recirculations is not limited by dispersion and for higher recirculation the following steps are devised: i) reducing the insertion loss and noise figure of the fiber optic link, and ii) flattening the frequency response of the closed loop system. Therefore, our

approach involves optimizing the performance of the fiberoptic delay element over the bandwidth of 2-4 GHz. A fiberoptic link is established over 2-4 GHz with a measured frequency response of the fiberoptic link has insertion loss of –11dB with flatness of 4dB was. The fiberoptic link has a compression dynamic range of 134 dB.Hz and spurious free dynamic range of 87 dB.Hz$^{2/3}$. A low noise figure fiber optic delay element is capable of recirculating a short electrical pulse as long as a millisecond, using 1 km optical delay line. The spectral purity of the recirculated signal is evaluated using the phase coherency measurement criteria. A plot of the phase noise degradation of the microwave carrier at three different recirculation times and offset carrier is shown in Fig. 10, where the spectral purity of the output pulses are shown after 10, 20, and 35 recirculations. The phase noise degradation is measured for offset carrier frequencies of 10, 50 and 100 Hz.

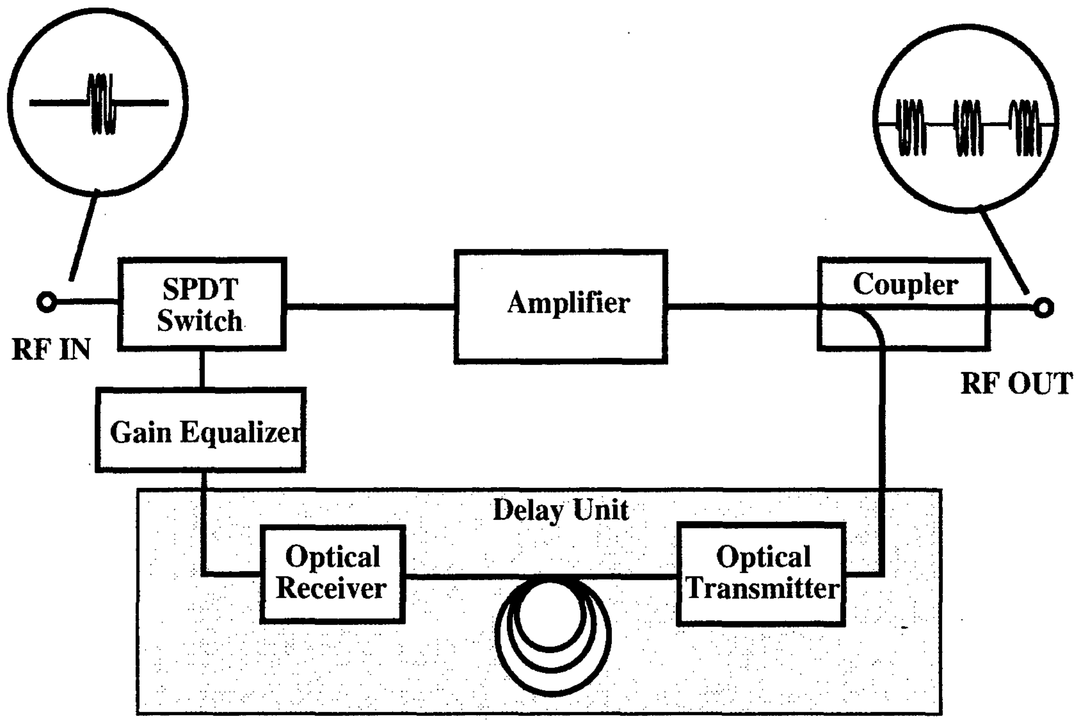


Fig. 9. Conceptual drawing of a fiberoptic based recirculating delay line. It is composed of a SPDT switch, electronic amplifier, coupler, optical delay element, and gain equalizer.

Since the frequency response of the open loop is not, in practice, flat over the bandwidth, for enhancing the performance of the memory loop, a gain equalizer is required. The amplification of the recirculating signal can be realized in either the electrical [7] or the optical domain. For broadband microwave signal processing, however, where the incoming signals in the frequency range of 2-18 GHz are analyzed, pulse recirculation in the optical domain is preferable to the electrical domain.

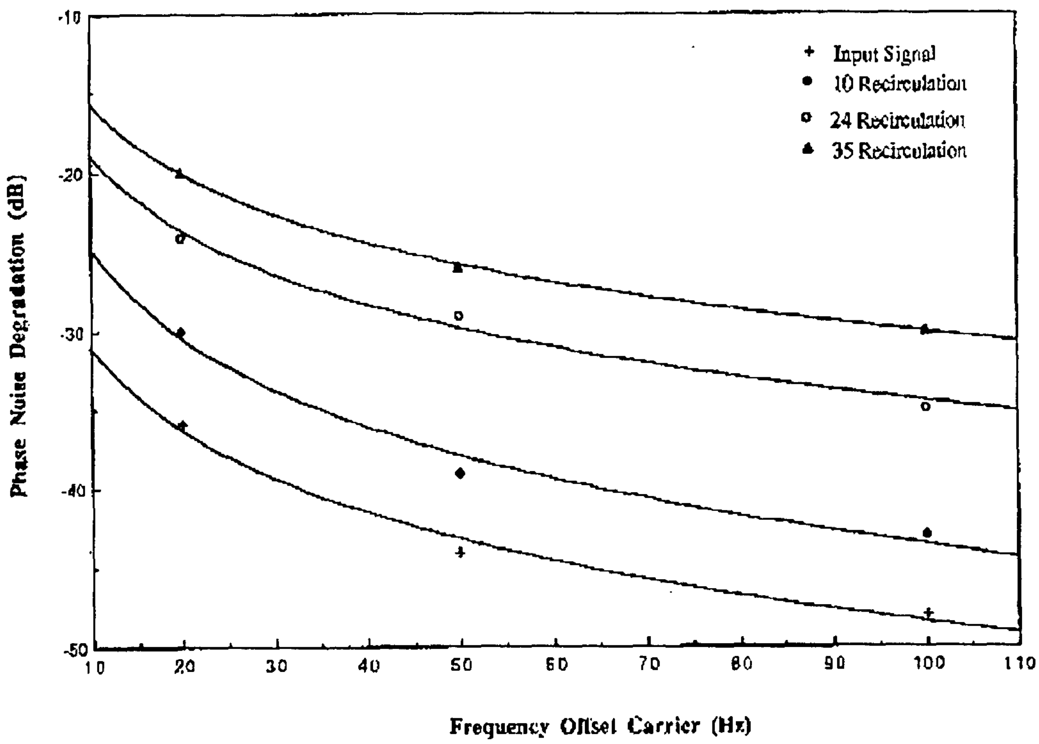


Fig. 10. Spectral purity and phase noise degradation compared to the input electrical pulse at various offset carrier as a function of number of recirulations.

The most limiting factor that degrades the output signal of the optical delay element is the noise build-up in the loop, whenever open loop gain is above unity. In particular, flatness and the noise figure are the limiting factors of Fiber Optic Memory Loop (FOML). The implication of non-flat frequency response of the delay unit is that the noise will increase faster at frequencies where the loop gain is high. Therefore, the nonflat frequency and high noise figure of the delay element will restrict the maximum number of recirculation attainable by the memory loop. The maximum number of recirculations in the loop in terms of the characteristics of the system components can then be numerically evaluated as a function of gain flatness, C. Particularly, the maximum number of recirculations, n_{max}, is limited to maximum number allowable by NF_{Tmax}, and the open loop noise figure NF_B as [7]:

$$NF_{Tmax} \approx \frac{1}{2}(NF_B-1)\left[\frac{1}{C^n}\frac{1-C^n}{1-C}+n\right]$$

The implication of non-flat frequency response of the delay unit is that the noise will increase at a faster rate at frequencies where open loop gain is greater than unity. Therefore, the non-flat frequency response and high noise figure of the delay element will restrict the maximum time delay attainable by the memory loop. Naturally, to overcome the n_{max} limitation, while achieving long total time delays, $n\tau$, one could increase the unit time delay, τ, but the long unit delay will produce a void in the time domain for the short input pulses. As an example, for the specified $(S/N)_{out}$=10 dB in a fiberoptic based memory loop using a

commercial FO link (Ortel link depicted in Table II), the maximum number of recirculation reduces from 954 for a flat frequency response to only 26 for a gain flatness of 1 dB. Whereas in case of reactively matched optical transmitter, the maximum numbers are 3070 and 37, respectively, because of the lower loss and noise figure of the fiberoptic link. Using a high gain reactively matched transmitter and an actively matched receiver leads to an unprecedented number of recirculation. Once again as, the link flatness reduces to 1dB of ripple, the maximum number of recirculation achieved would reduce to only 46 times. An adaptive gain equalization technique can be used to suppress the effect of noise build up in the system, which is enhanced by non flatness of the frequency response of the loop.

The maximum number of recirculation in the optical domain can be analyzed based on the noise performance of the commercially available optical amplifiers. The noise build-up in the optical system depends on many parameters such as optical power level, laser modulation index, light coupling factors, and quantum efficiencies of electro-optic transducers. Noise contribution of the spontaneous-spontaneous beat noise of the optical amplifier to the overall noise can be minimized by a reduction of the enormous gain bandwidth (>6000GHz) of the optical amplifier (to <100GHz).

For the memory loop system with narrow optical bandwidth, the major noise source of the system is signal-spontaneous beat noise. In this case, the maximum number of recirculations in the optical memory loop is dependent on the signal level and modulation index of the optical transmitter. As an example, a commercially available optical amplifier with the following characteristics is considered. The optical amplifier has internal gain of 15dB, saturation output power of 5 mW, noise enhancement factor of 2, and input and output coupling efficiencies of 33%. The signal-to-noise ratio was calculated as a function of number of recirculations with modulation index as a parameter. A plot showing the output signal-to-noise ratio for the internal gain of 15 dB is depicted in Fig. 11. In this figure modulation indexes of 0.1, 0.2, 0.3, 0.5, 0.75 and 1 are selected. Also shown here is the output signal-to-noise ratio of 6 dB, which corresponds to the minimum signal-to-noise ratio requirement for efficient detection. From this figure, based on a modulation index of 0.3, and for signal-to-noise ratio to be degradated to 6 dB, the maximum number of recirculations, as high as $n_{optical}$= 750, is obtained. This number shows that when the optical loop is operated at the proper bias and signal level for unit delay element of 1km, time delay in the range of millisecond can easily be achieved. However, as the optical gain increases, the number of optical recirculation diminishes precipitously.

Advanced Optical Signal Processing Techniques: The use of passive optical components such as optical isolators, array wave guide grating, superposed array grating, and spatial light modulators enable us now to perform a number of signal processing techniques to mitigate interference [8- 10], and adaptive waveform generation [11]. The basic principle of these techniques are based on translating spectrum to time using dispersive fibers or delay lines. As the number of taps increases, increased resolution in frequency domain could be observed. On the other hand, using mode-locke dpulses with short sampling period will increase the time resolution. As the tap weights and unit time delay are adjusted, aribtary waveform in time domain are generated that corresponds to the desired transfer function. Fig. 12 depicts structure of a tunable filter and a tunable filter Q as high as 800 has been demonstrated by Prof. Minasian. Even though discrete grating arrays are simpler in design and implementation, but for sampling bandwidth in the range of THz, superposed arrays are quite practical [12].

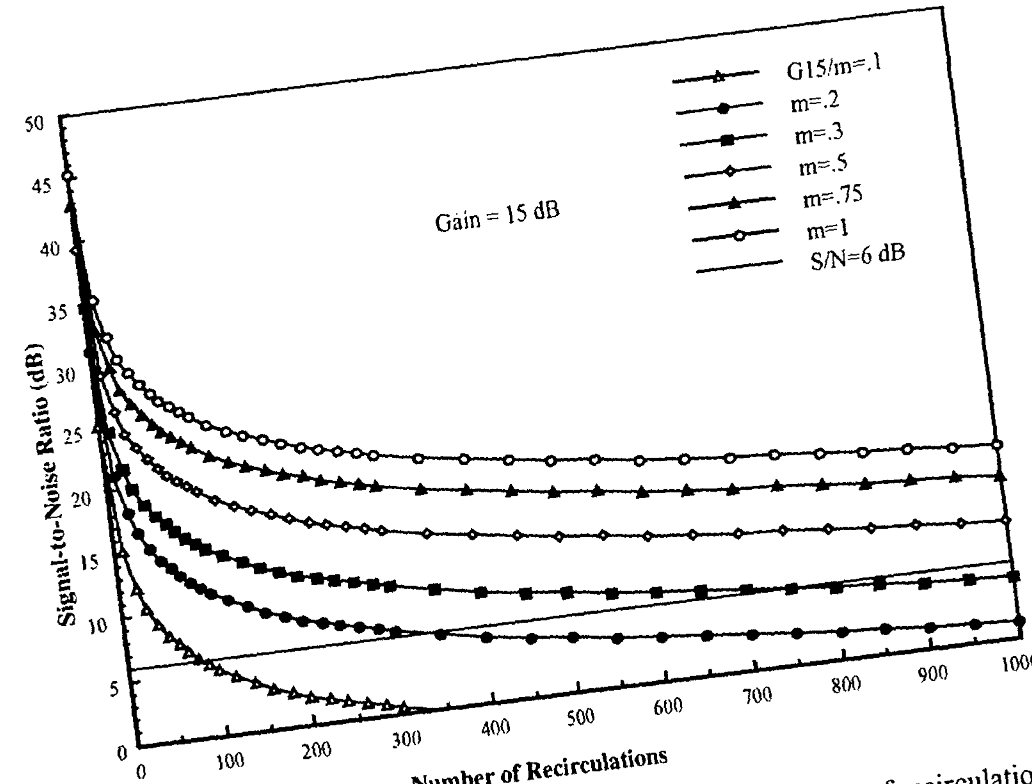
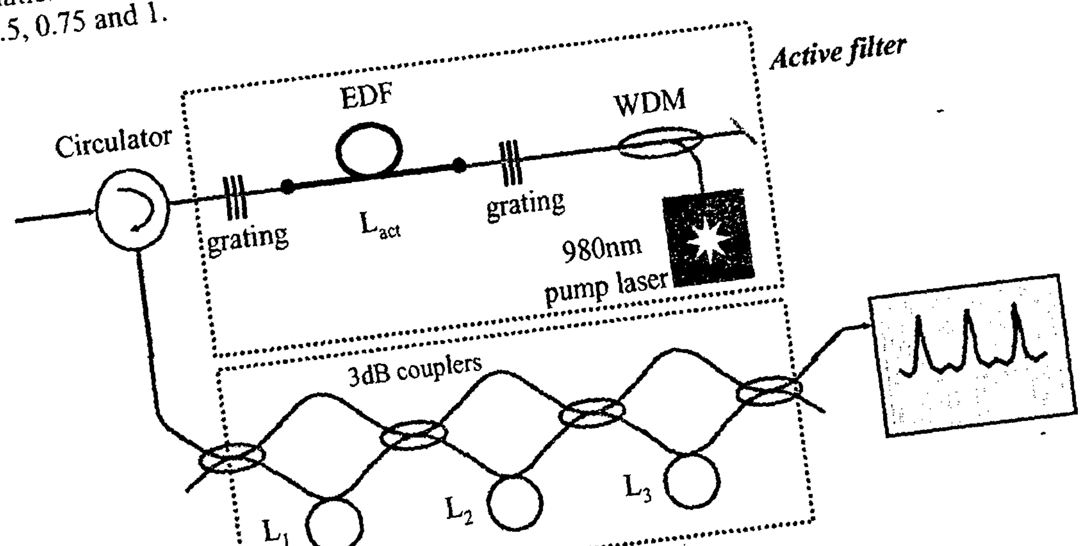


Fig. 11. Signal-to-noise ratio in an optical loop as a function of number of recirculations with modulation index as parameter. Amplifier gain is 15 dB and modulation indexes are 0.1, 0.2, 0.3, 0.5, 0.75 and 1.



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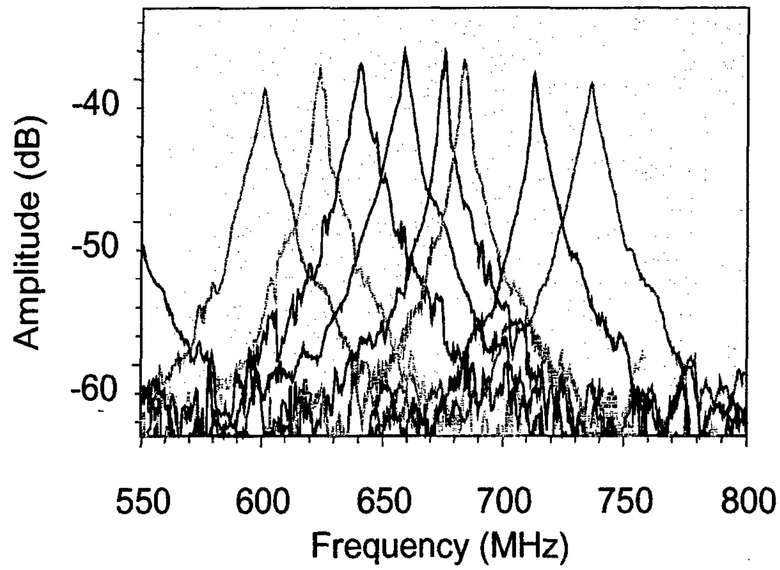
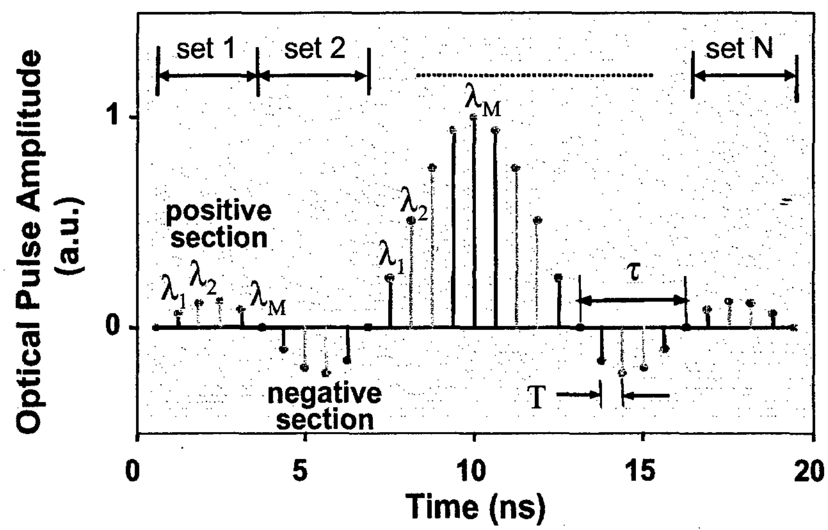


(b)

Fig. 12. Optical signal processing using a tunable filter. a) Experimental set-up, b) transfer function in terms of modulated frequency. (Courtesy of Prof. Robert Minasian of University of Sydney.)

Moreover, tapped delay line are employed in combination with positive and negative optical amplitude to adjust transfer function and shape of the transversal filter. High birefringence material combined with polarizer to create all optical transversal filters. Fig. 13 renders the shape of filter impulse response. The desired impulse response is converted to the desired bandpass filter. Moreover, notch filters could be developed using RF interference in the optical fiber while the other frequencies are transmitted through without much attenuation. Interference mitigation of 50dB at 75 MHz is experimentally demonstrated by Prof. Minasian.



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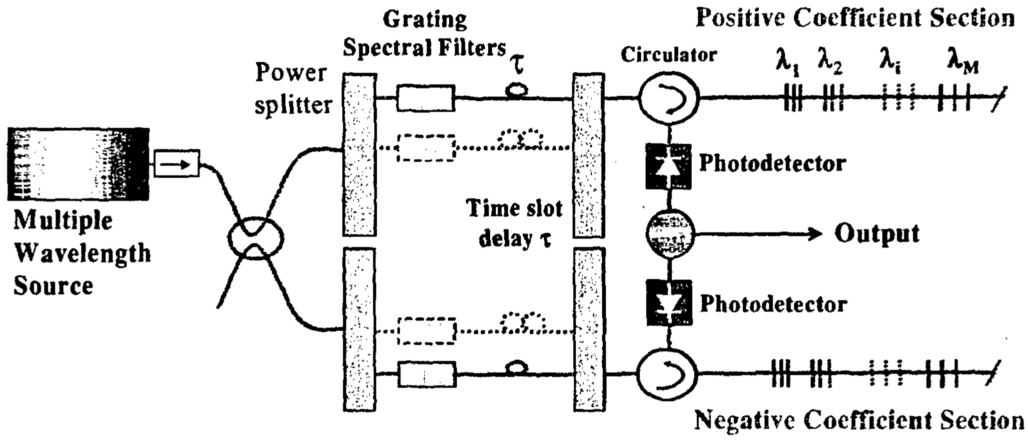

Fig. Filter Impulse Response (FIR) using spectral time mapping. a) Desired signal in time domain, and b) experimental set-up. (Courtesy of Prof. Robert Minasian of University of Sydney.)

5.0. CONCLUSIONS

This paper provides a personal perspective of microwave photonics and its direction of maturity. The direction of research is to develop novel devices that could meet high performance and low cost expectation. The harsh military environment also impacts the architecture of fiberoptic distribution networks. Among technologies that are unique to microwave photonics is the issue of optical signal processing which could lead to very large time-bandwidth products, hence resulting in high frequency selectivity. Memory loop devices, transversal filters, tapped delay lines are attractive solution that commands nitch market over the electrical signal processing techniques.

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REFERENCES

[1] H.X. Shi, D.A. Cohen, J. Barton, M. Majewski, L.A. Coldren, M.C. Larson, G.A. Fish, "Dynamics range of widely tunable sampled grating DBR lasers," *Electron Lett.*, Vol 38, pp. 180-181, Feb. 2002.

[2] A. S. Daryoush, K. Sato, K. Horikawa, and H. Ogawa, "Dynamic Response of Long Optical Cavity Laser Diode for Ka-band Communication Satellites," *IEEE Trans. Microwave Theory and Techniques*, Vol. 45, no. 8, pp. 1288-1295, August 1997.

[3] R. Saedi, W. Jen, N. Samant, A.S. Daryoush, D. Sturzebecher, P. Herczfeld, "Comparison of CPU Level data Mixing to T/R Level Data Mixing Architectures in Optically Controlled Phased Arrays," *The 1993 International Microwave Symposium,* Atlanta, GA, June 1993.

[4] X. Zhang and A.S. Daryoush, "Full 360^{o} Phase Shifting of Injection Locked Oscillators," *IEEE Microwave and Guided Wave Letters,* vol. 3, no. 1, pp. 14-16, 1993.

[5] X. Zhou and A. S. Daryoush, "An Efficient Self-Oscillating Mixer for Communications" *IEEE Trans. Microwave Theory and Techniques,* vol. 42, no.10, pp.1858-1862, Oct. 1994.

[6] A. S. Daryoush, K. Sato, K. Horikawa, and H. Ogawa, "Efficient Optoelectronic Mixing at Ka-Band Using a Mode-Locked Laser," *IEEE Microwave and Guided Wave Letters*, Vol. 9, no. 8, pp. 317-319, August 1999.

[7] R. Saedi, A.S. Daryoush, and P. Herczfeld, "Fiberoptic Based Recirculating Memory Loop" The 1992 *IEEE International Microwave Symposium Digest, 1992 IEEE MTT-S Microwave Symposium Digest*, vol. II, pp. 677-680, Albuquerque, NM, June 1992.

[8] D.B. Hunter, R.A. Minasian, P.A. Krug, "Tunable Optical Transversal Filter Based on Chirped Gratings," *Electron Lett.*, vol. 31, pp.2205-2207, 1995.

[9] J. Campany, D. Pastor, B. Ortega, "New and Flexible Fiberoptic Delay Line Filters using Chirped Bragg Gratings and Laser Arrays," *IEEE Trans Microwave Theory Techn.*, Vol. 47, pp. 1321-1326, 1999.

[10] X. Wang and K.T. Chan, "Tunable All-Optical Incoherent Bipolar delay-Line Filter using Injection-locked FP laser and Fiber Bragg Gratings," *Electron Lett.*, vol. 36, no.24, 2000.

[11] A.M. Weiner et al, IEEE J. Quantum Electron, vol. 28, p. 908, 1992.

[12] R.A. Minasian, K.E. Alameh, and E.H.W. Cahan, "Photonics-based Interference Mitigation Filters", *IEEE Trans on Microwave Theory & Techn.*, Special Issue on Microwave and Millimeter-wave Photonics, Vol. 49, No. 10, pp. 1894-1899, 2001.